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THE EFFECT OF TRAFFIC UPON RUNWAY PAVEMENT CROSS-SECTION

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THE EFFECT OF TRAFFIC UPON RUNWAY PAVEMENT CROSS-SECTION[a]

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Associate Members, ASCE

The past decade has seen great increases in airport traffic and in the size of aircraft which make up this traffic. These trends have led to larger and larger investments in airport runways. The prospect of further airport expansions indicates the desirability of appraising runway design with a view to obtaining maximum load-handling capacity per dollar.

It is common practice to make the thickness of airport runway pavement uniform across the width of the runway. Observation of skid marks had indicated that traffic on the runway is fairly well centered. The traffic distribution for military airfields was observed in this manner by Hibbert Hill about ten years ago.[1] This investigation was therefore undertaken to determine the actual transverse distribution of traffic at civil airports and to relate this distribution to pavement thickness, no attempt was made to determine the distribution of traffic in a longitudinal direction.

The Los Angeles, Oakland, and San Francisco airports were selected for study. Traffic distribution was observed and compared for day and night operations under both visual and instrument flight conditions.

The transverse distributions were determined at three locations on the runway by means of electrical traffic detector tapes. These tapes, located at 600 ft, 1000 ft, and 1800 ft from the end of the runway, were capable of determining the transverse position of a wheel within 10 ft. From the distribution of wheel loads an attempt was made to develop a design for runway pavement of varying thickness.

Method of Conducting Tests

The tape locations were selected so as to detect significant variations in the transverse distributions along the runway.

A search of the literature disclosed previous work by the U. S. Civil Aeronautics Administration[2] in which the touchdown position, in terms of

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a. A paper prepared for presentation at the Annual Meeting of the American Society of Civil Engineers, San Diego, Calif., February, 1955.

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1. Hill, Hibbert, Discussion of Paper No. 2247, "Military Airfields, A Symposium," Transactions, vol. 110, 1945, American Society of Civil Engineers. pp 758-763.
2. U. S. Civil Aeronautics Administration, Airport Engineering Bulletin No. 1. June 15, 1951.

distance from the end of the runway, was obtained for nearly 1000 landings. On the basis of these observations positions of three detector tapes were established; these locations are shown in Fig. 1. It was anticipated that the first tape, 600 ft from the runway end, would detect the transverse position of 100 percent of all aircraft taking off and approximately 20 percent of all aircraft landing. The second tape, 1000 ft from the runway end, would account for nearly all take-offs and 65 percent of the landings. The third tape, 1800 ft from the runway end, would detect approximately 75 percent of all aircraft taking off and nearly all of the aircraft landing.

The problem of determining the transverse position of highway vehicles had been studied at the Institute of Transportation and Traffic Engineering, University of California at Los Angeles, and a segmented electrical detector tape developed.[3] The tape, shown in Fig. 4, consists of two spring-steel elements which are normally held open by means of a gum-rubber spacer strip. The bottom contact extends throughout the length of the unit and serves as a common contact for all segments. The upper contact was made in 10-ft lengths.

Runway widths were 150 ft and 200 ft. For adequate coverage each tape was made 160 ft long and divided into 16 segments of 10 ft. Since many of the dual-wheel landing-gear assemblies are nearly 4 ft in width it was felt that the accuracy gained by dividing the tapes into smaller segments was not warranted. A typical installation of one of the tapes is shown in Fig. 2.

The tapes were attached to the runway with a rubber cement and covered with two layers of industrial adhesive tape. The units proved remarkably resistant to abrasion and only occasional patching with additional adhesive tape was necessary to provide satisfactory protection for the electrical units. A circuit was designed to indicate which segment was occupied by the left-hand wheel of moving aircraft. The indicator, which was stationed opposite the center detector tape, is shown in Fig. 3. It consists of 16 lighted neon tubes, each representing a 10-ft segment of tape. As the left wheel of the aircraft rolled across a particular 10-ft segment all tubes associated with segments to the left of that contacted remained lighted. It was necessary to reset the neon-tube indication after the aircraft had passed each tape in succession but the time between crossings of the detector tapes was sufficient to obtain a reading and clear the circuit for the next tape.

Test Program

Observations were made during September and October 1953. At each airport both night and daytime movements both under visual and instrument conditions were observed for all transport aircraft. Data recorded were time of landing, or take-off, type of aircraft, whether movement was made under visual or instrument regulations, and the appropriate indication of transverse position as the aircraft crossed each of the three detector tapes. Wind velocity and direction were noted as these data were reported to pilots.

The runways on which traffic tapes were placed at the three airports, and their principal characteristics are tabulated below.

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3. Mathewson, J. H., Brenner, R., and Reiss, R. J. "A Segmented Electrical Element for Detecting Vehicular Traffic," Proceedings, Highway Research Board, 1949, pp. 374-383.

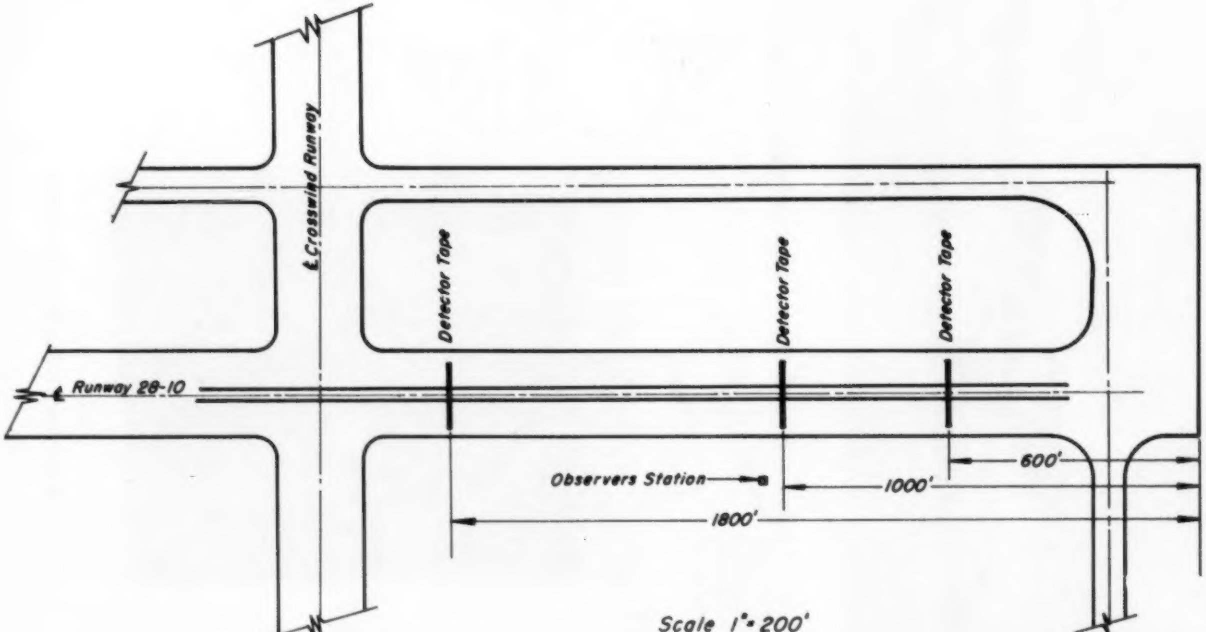


Fig 1-LOCATION OF DETECTOR TAPES ON RUNWAY.

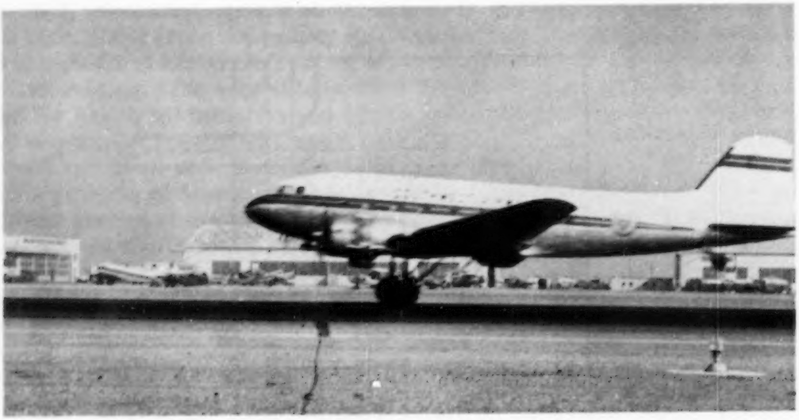


Fig. 2. Field Installation of Detector Tape at Oakland Airport.

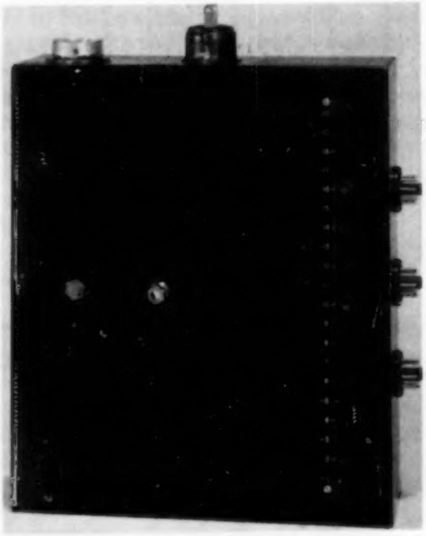


Fig. 3. Transverse Position Indicator.

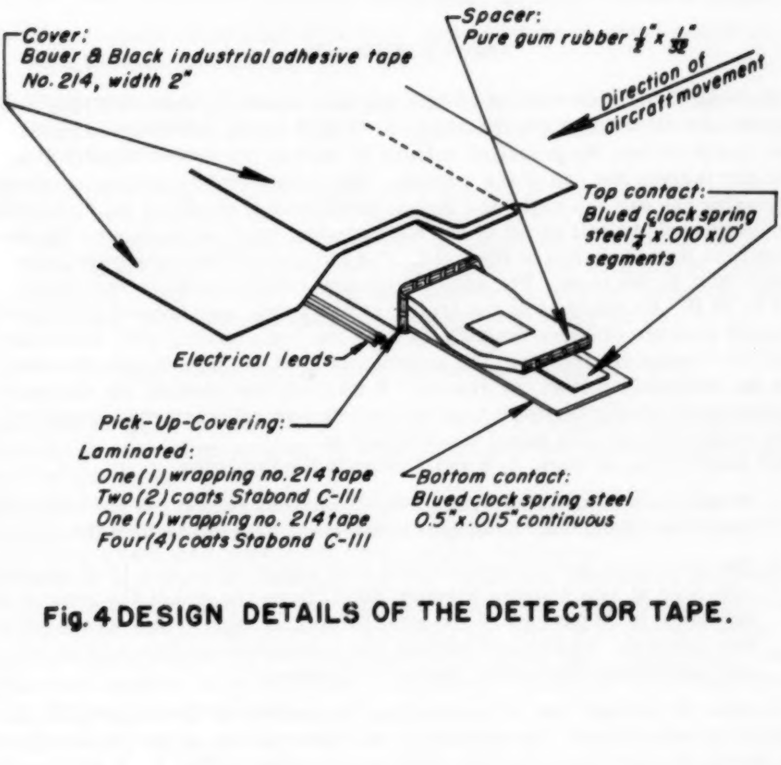


Fig. 4 DESIGN DETAILS OF THE DETECTOR TAPE.

TABLE 1

Airport	Runway	Width	Length	Total Movements
Los Angeles International	25R	150 ft	8500 ft	263
Oakland Municipal	27R	150	5500	267
San Francisco International	28R	200	8900	228

Total movements refer to landings or take-offs. Since all aircraft did not contact all three detector tapes due to landing long, short take-off runs, or bouncing over a tape, the total movements of each tape are not the same as the total movements listed in Table 1.

Analysis of Results

The results of observations at Los Angeles, Oakland, and San Francisco airports are shown on Figs. 5 through 9. Fig. 5 shows the distribution of wheel loads across the principal runway at each of the three airports at a point 600 ft from the end of the runway. The figure covers landings and take-offs during the day and night and during conditions of good and poor visibility. The position of the left wheel of the main landing gear as it crossed the detector tape was observed in the field. The position of the right wheel was plotted 20 ft to the right. The actual distances between wheels vary from 18 ft to 28 ft. An analysis of the traffic at San Francisco Airport indicates a weighted average of approximately 23 ft as the main landing gear tread distance for transport aircraft. The adoption of 20 ft as the average distance does not seriously distort the results. It was felt that plotting the distance between main wheels for each type of aircraft was not warranted since the exact position of the left wheel was not known.

An examination of Figs. 5, 6 and 7 reveals the following.

1) Traffic is concentrated within a 60-ft width of runway, at the three tape locations. Less than 5 percent of the traffic occurs beyond these limits.

2) The maximum percentage of wheel load applications in a 10-ft segment occurred at Los Angeles Airport, 600 ft from the end of the runway and amounted to 28 percent of the total number of wheel loads recorded at this location. At Oakland Airport the corresponding figure is 26 percent and at San Francisco Airport 27 percent.

In order to indicate the variation along the runway of the transverse distribution of wheel loads, the average of the observations at the three airports was plotted for each detector tape position as shown in Fig. 8. It will be noted that the patterns are quite similar, indicating that the transverse distribution of wheel loads is approximately the same all along the runway.

In order to use the data for development of a proposal design an average distribution was worked out to represent all of the observations at the three airports. This distribution is shown in Fig. 9. The standard curve of error which best fitted all the observations was computed and the chart drawn. This procedure was used in preference to an arithmetic mean as the latter would not have properly accounted for the different numbers of observations at each airport.

The data in Fig. 9 suggest that the pavement for the central 60-ft portion

of a runway could be designed for 25 percent of the total number of wheel load applications which the runway would receive during its economic life. The remainder of the runway width would be designed for 3 percent of the wheel load applications. It is recognized that 25 percent applied to the entire 60-ft portion is conservative since only the 10-ft segment near the center line carries the 25 percent; however, a finer breakdown is not warranted at this time as only three airports have been investigated. Further, the design criteria outlined are conservative in that traffic loading will be less at the upwind end of the runway than at the end at which most landings and take-offs occur.

At the start of the tests it was believed that visibility and cross-winds might affect the pattern of wheel load distribution on a runway, therefore data on wind conditions and visibility were recorded in the field. An analysis of the observations indicates the following:

1) There was no significant difference in the pattern of wheel load applications between night and day.

2) There was no significant difference in the pattern of wheel load applications between a visual approach and an approach made under instrument conditions.

3) Within the range of cross-wind velocities encountered, up to 15 mph, there was no observable effect upon the pattern of wheel load application. In several instances, however, incoming aircraft had to make several approaches in order to compensate for the wind before touching down on the runway. When they did touch down their positions were not materially different than those observed at other times.

Application of Results to Pavement Thickness

In order to apply the data to the determination of pavement thickness it is necessary to use design procedures which include wheel load repetitions as one of the variables.

For the purpose of this paper the procedure developed by F. N. Hveem and his associates in the California Division of Highways[4] was used to show the effect of wheel load repetitions on pavement thickness.

Data from test tract studies made by the California Division of Highways and others have indicated that the destructive effect of wheel loads varies as the square root of the magnitude of the loads, and that the necessary thickness of pavement varies as the logarithm of the wheel load repetitions. The relationship between wheel loads and repetitions used by the California Division of Highways is as follows:

$$\sqrt{W_1}\ \log r_1 = \sqrt{W_2}\ \log r_2$$

where W_1 and W_2 = wheel loads, lb

r_1 and r_2 = repetitions of wheel loads W_1 and W_2

4. Hveem, F. N. and Carmany, R. M. "The Factors Underlying the Rational Design of Pavements," Proceedings, Highway Research Board, 1948, pp. 101-136.

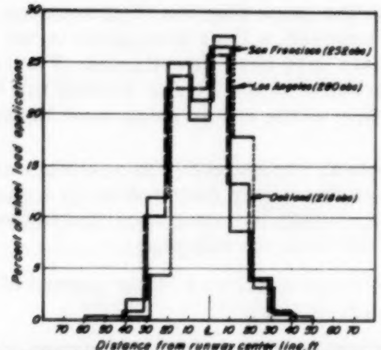


Fig. 5 DISTRIBUTION OF WHEEL LOAD APPLICATIONS 600FT FROM END OF RUNWAY AT LOS ANGELES, OAKLAND AND SAN FRANCISCO AIRPORTS.

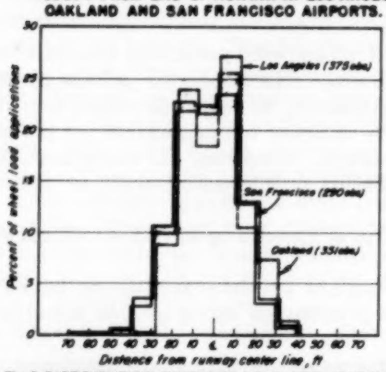


Fig. 6 DISTRIBUTION OF WHEEL LOAD APPLICATIONS 1000FT FROM END OF RUNWAY AT LOS ANGELES, OAKLAND AND SAN FRANCISCO AIRPORTS.

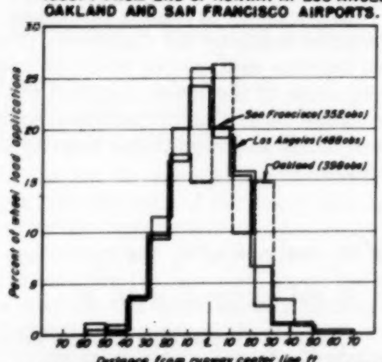


Fig. 7 DISTRIBUTION OF WHEEL LOAD APPLICATIONS 1800FT FROM END OF RUNWAY AT LOS ANGELES, OAKLAND AND SAN FRANCISCO AIRPORTS.

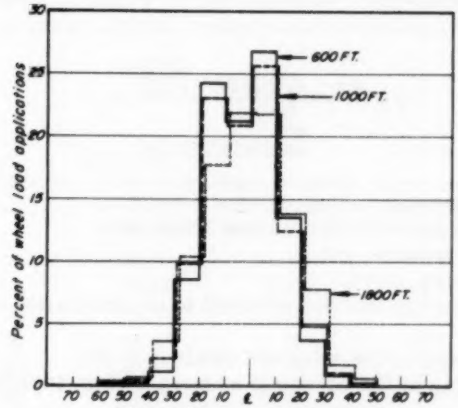
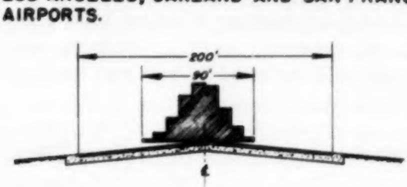


Fig.8 DISTRIBUTION OF WHEEL LOAD APPLICATIONS AT 600 FT, 1000 FT, AND 1800 FT FROM END OF RUNWAY, AVERAGE OF OBSERVATIONS AT LOS ANGELES, OAKLAND AND SAN FRANCISCO AIRPORTS.



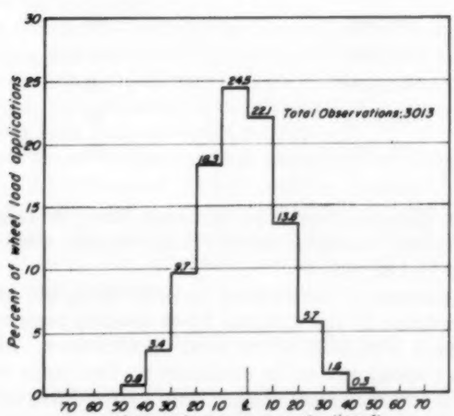


Fig.9 DISTRIBUTION OF WHEEL LOAD APPLICATIONS, AVERAGE OF ALL OBSERVATIONS AT LOS ANGELES OAKLAND AND SAN FRANCISCO AIRPORTS.

By application of this relationship all wheel loads can be converted to repetitions of a single arbitrarily selected wheel load.[5]

The equation for pavement thickness developed by the California Division of Highways, presented in nomograph form in Fig. 10, is as follows:

$$T = \frac{(KP\sqrt{a}\,\log r)^{\frac{(90-R)}{(100)}}}{\sqrt[5]{c}}$$

where

T = thickness of pavement, in.
K = 0.016 for best correlation with test track data.
P = contact tire pressure, psi.
a = contact tire area, sq in.
r = number of load applications adjusted to an arbitrarily selected wheel load.
R = resistance value of the subgrade (scale 0 to 90).
c = tensile strength of the pavement as measured by cohesiometer.

Suppose a runway is to be designed as a flexible type pavement for 180,000 aircraft movements annually. The bearing capacity of the subgrade in terms of resistance value R is 35, which is approximately equivalent to a California Bearing Ratio of 5 or 6 percent. The economic life of the pavement is assumed as 10 years so the total number of wheel load applications on the runway will be 3,600,000. A record of landings and take-offs at the field indicates that the new runway will be used by aircraft having the following average weights.

Gross Weight of Aircraft, lb	Percent of Total Traffic
140,000	5
96,000	20
70,000	15
40,000	10
25,000	15
10,000	35

For the purpose of this problem it is assumed that the weight of the aircraft is distributed equally between the two main wheels and that the average tire contact pressure is 100 psi.

The central 60-ft portion of the runway is to be designed on the basis of the wheel load applications on the critical 10-ft central segment. This segment carries 25 percent (900,000) of the total applications. Similarly, the outer portions of the runway are to be designed on the basis of a 10-ft segment which is critical for those portions. This critical segment carries 3 percent (108,000) of the total load applications.

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5. Suppose it was desired to know the number of repetitions of a 50,000-lb load which would have the same destructive effect as 10,000 repetitions of a 20,000-lb load.

Then $\sqrt{20,000}\,\log\ 10,000 = \sqrt{50,000}\,\log r_{50,000}$ from which $r_{50,000} = 338$

A 50,000-lb load was chosen arbitrarily as the common denominator for the determination of wheel load applications for use in the formula for pavement thickness. The result would have been the same regardless of the wheel load selected. The equivalent repetitions of a 50,000-lb load were computed as previously described and the results summarized in Table 2.

TABLE 2

Wheel Load lb.	Percent of Total Loads	900,000 Applications: Wheel Load Applications	900,000 Applications: Equiv. 50,000 lb. Applications	108,000 Applications: Wheel Load Applications	108,000 Applications: Equiv. 50,000 lb. Applications
70,000	5	45,000	319,700	5400	26,030
48,000	20	180,000	141,300	21,600	17,690
35,000	15	135,000	19,680	16,200	3,337
20,000	10	90,000	1352	10,800	354
12,500	15	135,000	367	16,200	127
6,000	35	315,000	54	37,800	28
	100	900,000	482,453	108,000	47,566

Using the nomograph, Fig. 10, we obtain a pavement thickness of 36 in. for 482,000 applications of a 50,000 lb wheel load, an R value of 35, a cohesiometer value of 300, and a contact pressure of 100 psi. Similarly, for 48,000 applications of the same wheel load a pavement thickness of 30 in. is indicated.

The cohesiometer value will vary for each particular design depending on the thickness and character of the surfacing and the base, it can vary from a little over 100 to as high as 1000. For the purpose of this problem a value of 300 was selected to represent the combined tensile strength of the bituminous surfacing and the base course.

The pavement thickness derived by the procedure is conservative. Inasmuch as the landing gear assemblies used on transport aircraft are not over 4 ft wide and the detector tapes were in 10-ft segments, the wheel loads, as was assumed in the computations, are not applied to the same pavement area in a 10-ft segment with each aircraft movement.

A suggested pavement cross-section based on the foregoing analysis is shown in Fig. 11. It consists of a 60-ft central section of 3 in. of bituminous plant mix, 9 in. of stabilized aggregate base course, and 24 in. of selected quarry-run material. The outer portions of the runway width consist of 2 in. of bituminous plant mix, 7 in. of stabilized aggregate base course, and 21 in. of selected quarry-run material.

Economic Considerations

In order to give some notion of the saving in cost which might be effected by a variable-thickness section as compared with a uniform section, costs were estimated for a runway 200 ft wide and 8000 ft long with alternate pavements: (1) a uniform thickness of 36 in. and (2) a thickness of 36 in. in the central 60 ft and a thickness of 30 in. in the remaining 140 ft. These estimates are summarized as follows:

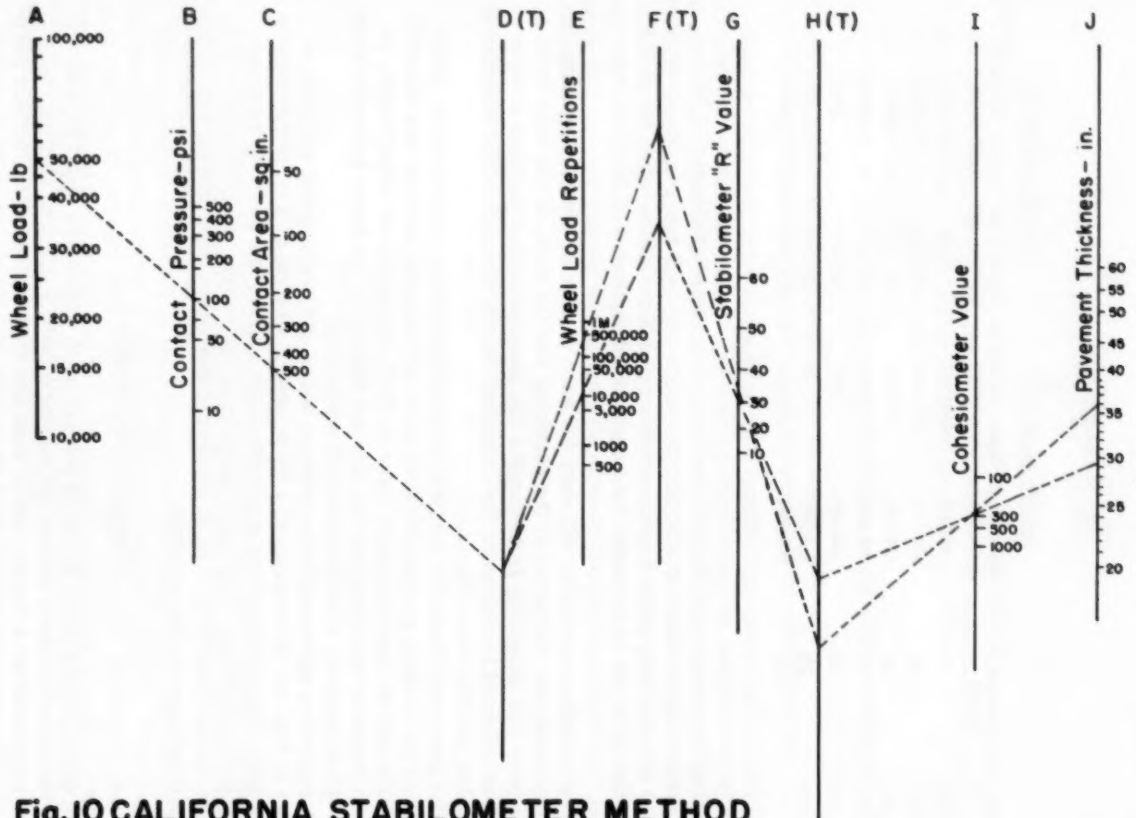

Fig. 10 CALIFORNIA STABILOMETER METHOD PAVEMENT THICKNESS CHART.

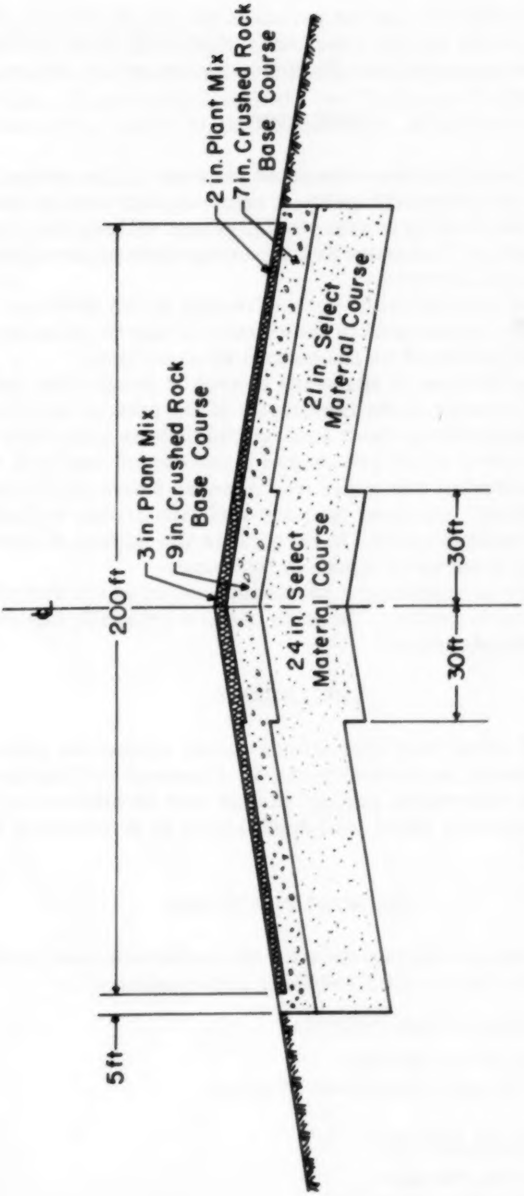

Fig. 11 SUGGESTED RUNWAY SECTION

(1) Uniform thickness pavement	$724,000
(2) Variable thickness pavement	$621,000
Saving in cost	$103,000

In making these estimates current prices in the San Francisco Bay Area were used; namely $6.50 per ton for bituminous plant mix; $2.60 per ton for stabilized aggregate base course; and $1.50 per ton for select material.

DISCUSSION

The foregoing analysis indicates some measure of the saving in cost that possibly could be made by taking into account the variation of load applications across the width of a runway. Such savings will naturally vary depending on the character of the native soil, the magnitude of the wheel loads, and the amount of traffic expected.

For the sake of simplicity the cost estimates do not take into account the fact that at taxiway connections to the runway it may be necessary to have the same thickness of pavement as the central 60-ft portion.

The California Division of Highways method of design was used for the example primarily because of the familiarity of the authors with this method. The basic data collected on wheel load applications is applicable to any pavement design procedure which recognized repetition of load as a variable.

The data presented in this paper was intended primarily for use in the design of civil airfields. On many military airfields groups of 2 or 3 aircraft use the runway simultaneously. In such cases the pattern of load distribution would be different from those shown in this paper.

In Fig. 11 there is suggested a pavement section which abruptly changes from one thickness to another. In some cases a gradually tapering section might be more advantageous.

CONCLUSIONS

The pattern of wheel load applications varies across the width of a runway and is concentrated in the central portion. A runway for transport aircraft is of such width that substantial savings in cost may be effected by taking into account this variation in wheel load applications in determining the thickness of the pavement.

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PROCEEDINGS-SEPARATES

The technical papers published in the past year are presented below. Technical-division sponsorship is indicated by an abbreviation at the end of each Separate Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways (WW) divisions. For titles and order coupons, refer to the appropriate issue of "Civil Engineering" or write for a cumulative price list.

VOLUME 80 (1954)

JUNE: 444(SM)[e], 445(SM)[e], 446(ST)[e], 447(ST)[e], 448(ST)[e], 449(ST)[e], 450(ST)[e], 451(ST)[e], 452(SA)[e], 453(SA)[e], 454(SA)[e], 455(SA)[e], 456(SM)[e].

JULY: 457(AT), 458(AT), 459(AT)[c], 460(IR), 461(IR), 462(IR), 463(IR)[c], 464(PO), 465(PO)[c].

AUGUST: 466(HY), 467(HY), 468(ST), 469(ST), 470(ST), 471(SA), 472(SA), 473(SA), 474(SA), 475(SM), 476(SM), 477(SM), 478(SM)[c], 479(HY)[c], 480(ST)[c], 481(SA)[c], 482(HY), 483(HY).

SEPTEMBER: 484(ST), 485(ST), 486(ST), 487(CP)[c], 488(ST)[c], 489(HY), 490(HY), 491(HY)[c], 492(SA), 493(SA), 494(SA), 495(SA), 496(SA), 497(SA), 498(SA), 499(HW), 500(HW), 501(HW)[c], 502(WW), 503(WW), 504(WW)[c], 505(CO), 506(CO)[c], 507(CP), 508(CP), 509(CP), 510(CP), 511(CP).

OCTOBER: 512(SM), 513(SM), 514(SM), 515(SM), 516(SM), 517(PO), 518(SM)[c], 519(IR), 520(IR), 521(IR), 522(IR)[c], 523(AT)[c], 524(SU), 525(SU)[c], 526(EM), 527(EM), 528(EM), 529(EM), 530(EM)[c], 531(EM), 532(EM)[c], 533(PO).

NOVEMBER: 534(HY), 535(HY), 536(HY), 537(HY), 538(HY)[c], 539(ST), 540(ST), 541(ST), 542(ST), 543(ST), 544(ST), 545(SA), 546(SA), 547(SA), 548(SM), 549(SM), 550(SM), 551(SM), 552(SA), 553(SM)[c], 554(SA), 555(SA), 556(SA), 557(SA).

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VOLUME 81 (1955)

JANUARY: 583(ST), 584(ST), 585(ST), 586(ST), 587(ST), 588(ST), 589(ST)[c], 590(SA), 591(SA), 592(SA), 593(SA), 594(SA), 595(SA)[c], 596(HW), 597(HW), 598(HW)[c], 599(CP), 600(CP), 601(CP), 602(CP), 603(CP), 604(EM), 605(EM), 606(EM)[c], 607(EM).

FEBRUARY: 608(WW), 609(WW), 610(WW), 611(WW), 612(WW), 613(WW), 614(WW), 615(WW), 616(WW), 617(IR), 618(IR), 619(IR), 620(IR), 621(IR)[c], 622(IR), 623(IR), 624(HY)[c], 625(HY), 626(HY), 627(HY), 628(HY), 629(HY), 630(HY), 631(HY), 632(CO), 633(CO).

MARCH: 634(PO), 635(PO), 636(PO), 637(PO), 638(PO), 639(PO), 640(PO), 641(PO)[c], 642(SA), 643(SA), 644(SA), 645(SA), 646(SA), 647(SA)[c], 648(ST), 649(ST), 650(ST), 651(ST), 652(ST), 653(ST), 654(ST)[c], 655(SA), 656(SM)[c], 657(SM)[c], 658(SM)[c].

APRIL: 659(ST), 660(ST), 661(ST)[c], 662(ST), 663(ST), 664(ST)[c], 665(HY)[c], 666(HY), 667(HY), 668(HY), 669(HY), 670(EM), 671(EM), 672(EM), 673(EM), 674(EM), 675(EM), 676(EM), 677(EM), 678(HY).

MAY: 679(ST), 680(ST), 681(ST), 682(ST)[c], 683(ST), 684(ST), 685(SA), 686(SA), 687(SA), 688(SA), 689(SA)[c], 690(EM), 691(EM), 692(EM), 693(EM), 694(EM), 695(EM), 696(PO), 697(PO), 698(SA), 699(PO)[c], 700(PO), 701(ST)[c].

JUNE: 702(HW), 703(HW), 704(HW)[c], 705(IR), 706(IR), 707(IR), 708(IR), 709(HY)[c], 710(CP), 711(CP), 712(CP), 713(CP)[c], 714(HY), 715(HY), 716(HY), 717(HY), 718(SM)[c], 719(HY)[c], 720(AT), 721(AT), 722(SU), 723(WW), 724(WW), 725(WW), 726(WW)[c], 727(WW), 728(IR), 729(IR), 730(SU)[c], 731(SU).

c. Discussion of several papers, grouped by Divisions.

e. Presented at the Atlantic City (N.J.) Convention in June, 1954.